The Astrophysical Journal, 654: L69–L72, 2007 January 1


# A PHYSICAL RELATIONSHIP BETWEEN ELECTRON-PROTON TEMPERATURE EQUILIBRATION AND MACH NUMBER IN FAST COLLISIONLESS SHOCKS

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*Received 2006 September 19; accepted 2006 November 9; published 2006 December 12*

## ABSTRACT

The analysis of Balmer-dominated optical spectra from nonradiative (adiabatic) SNRs has shown that the ratio of the electron to proton temperature at the blast wave is close to unity at $v_S \lesssim 400$ km s$^{-1}$ but declines sharply down to the minimum value of $m_e/m_p$ dictated by the jump conditions at shock speeds exceeding 2000 km s$^{-1}$. We propose a physical model for the heating of electrons and ions in non–cosmic-ray–dominated, strong shocks ($v_S > 400$ km s$^{-1}$) wherein the electrons are heated by lower hybrid waves immediately ahead of the shock front. These waves arise naturally from the cosmic ray pressure gradient upstream from the shock. Our model predicts a nearly constant level of electron heating over a wide range of shock speeds, producing a relationship $(T_e/T_p)_0 \propto v_S^{-2}$ ($\propto M^{-2}$) that is fully consistent with the observations.

*Subject headings:* cosmic rays — ISM: kinematics and dynamics — plasmas — shock waves — supernova remnants

## 1. INTRODUCTION

The discovery of collisionless shock waves in the solar wind in the 1960s ushered in a new era in the physics of space plasmas (see Tidman & Krall 1971, Sagdeev 1979, and Kennel 1985 for reviews and references). Due to the low density ($n \lesssim 1$ cm$^{-3}$) of the interplanetary medium, the jump in hydrodynamical quantities is produced not by Coulomb collisions but by collective plasma processes such as electromagnetic waves and turbulence. However, despite the availability of extensive in situ observations of solar wind shocks and the expenditure of considerable effort in theoretical modeling of these structures, a detailed understanding of the processes at the shock transition responsible for partitioning the shock energy between different charged particle species has been slow to emerge. The problem is far more acute for interstellar shocks, where in situ measurements of the shock structure are unavailable and the very high Mach numbers (∼30–200) make numerical simulations of these structures extremely difficult or impossible.

The optical emission generated by nonradiative supernova remnants (SNRs) in partially neutral gas provides a valuable diagnostic tool for probing the heating processes in collisionless shocks. The optical spectra of these SNRs (which lose a negligible fraction of their energy to radiation) are dominated by Balmer line emission, produced by collisional excitation when neutral hydrogen is overrun by the blast wave (Chevalier & Raymond 1978; Bychkov & Lebedev 1979). Each emission line consists of two components: (1) a narrow velocity component produced when cold, ambient H I overrun by the shock is excited by electron and proton collisions and (2) a broad velocity component produced when fast neutrals created by postshock charge exchange are collisionally excited (Chevalier et al. 1980). An example of a Balmer-dominated shock spectrum from the Galactic SNR RCW 86 is shown in Figure 1. The optical emission arises in a very thin ($\lesssim 10^{16}$ cm) ionization zone, thin enough so that the protons transformed into hot neutrals have had little time to equilibrate with electrons and other ions. This makes the measured width of the broad Balmer line directly proportional to the proton temperature set by collisionless heating at the shock front. The broad-to-narrow flux ratio, $I_B/I_N$, on the other hand, is sensitive to both the degree of electron-proton temperature equilibration at the shock front [i.e., $(T_e/T_p)_0$] and the shock velocity, $v_S$ (Chevalier et al. 1980; Smith et al. 1991). The ratio also depends (although less sensitively) on the preshock neutral fraction. The broad component width and $I_B/I_N$ of an observed Balmer-dominated shock can be modeled with numerical shock codes to simultaneously estimate $v_S$ and $(T_e/T_p)_0$ (Smith et al. 1991; Ghavamian 1999; Ghavamian et al. 2001, 2002).

In this Letter, we draw together observed values of $(T_e/T_p)_0$ and $v_S$ measured in five Balmer-dominated SNRs, including several previously unpublished measurements from the SNR RCW 86. We then propose a physical model of electron heating by lower hybrid waves in a cosmic ray precursor that obeys the observed relationship between $(T_e/T_p)_0$ and $v_S$. We conclude by exploring some consequences of this interpretation, the connection to other observables, and applicability to other collisionless shock situations.

## 2. RELATIONSHIP BETWEEN EQUILIBRATION AND SHOCK SPEED

In Figure 2, we plot 11 measurements of $(T_e/T_p)_0$ and $v_S$, obtained from long-slit spectra of four Galactic remnants: the Cygnus Loop (one position from the northeast), RCW 86 (positions from the southwestern, northern, and eastern limbs), Tycho's SNR ("knot g" from the eastern rim), SN 1006 (one position from the northwestern rim), and one remnant in the Large Magellanic Cloud, DEM L71 (five positions from the full circumference of the shell). In the first four remnants, the shock parameters have been estimated via long-slit spectroscopy. First, we used the broad component H$\alpha$ width to constrain the range of shock speeds for each Balmer filament in the limits of minimal [$(T_e/T_p)_0 = m_e/m_p$] and full [$(T_e/T_p)_0 = 1$] equilibration. Next, we fine-tuned $(T_e/T_p)_0$ and $v_S$ by using shock models to match the observed broad-to-narrow flux ratio (Ghavamian et al. 2001, 2002).

In the case of RCW 86, we have added two more data points, indicated by dashes in Figure 2, derived from previously unpublished optical spectra of Ghavamian (1999). These were obtained from the eastern rim [$v_{\rm FWHM}({\rm H}\alpha) = 640 \pm 35$ km s$^{-1}$;

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# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**SEP 2006** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2006 to 00-00-2006** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**A Physical Relationship Between Electron-Proton Temperature Equilibration and Mach Number in Fast Collisionless Shocks** | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Naval Research Laboratory,Washington,DC,20375** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR’S ACRONYM(S)<br>11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **4** | |

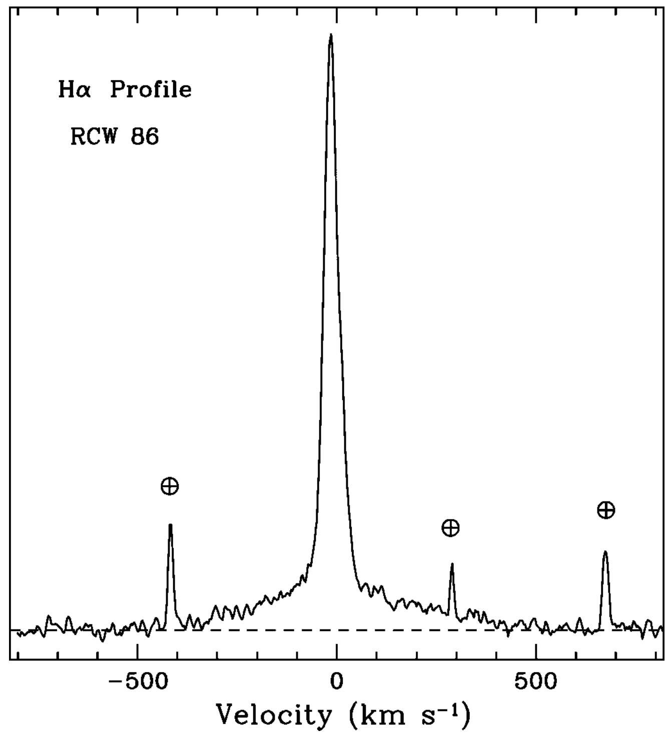


FIG. 1.—Example of the optical spectrum of a Balmer-dominated shock, showing the broad and narrow Hα lines characteristic of nonradiative shocks in partially neutral gas. This spectrum, originally presented by Sollerman et al. (2003), was obtained from the southwestern rim of the Galactic SNR RCW 86, with high enough spectral resolution (~10 km s$^{-1}$) to resolve the broad (~500 km s$^{-1}$ FWHM) and narrow (~30 km s$^{-1}$ FWHM) Hα lines. The night-sky OH lines (indicated by the circled plus signs) have been left in to demonstrate their relatively narrower widths compared to the Hα lines. The broad Hα width and ratio of the broad to narrow Hα flux for these types of shocks were used to produce the relationship shown in Fig. 2.

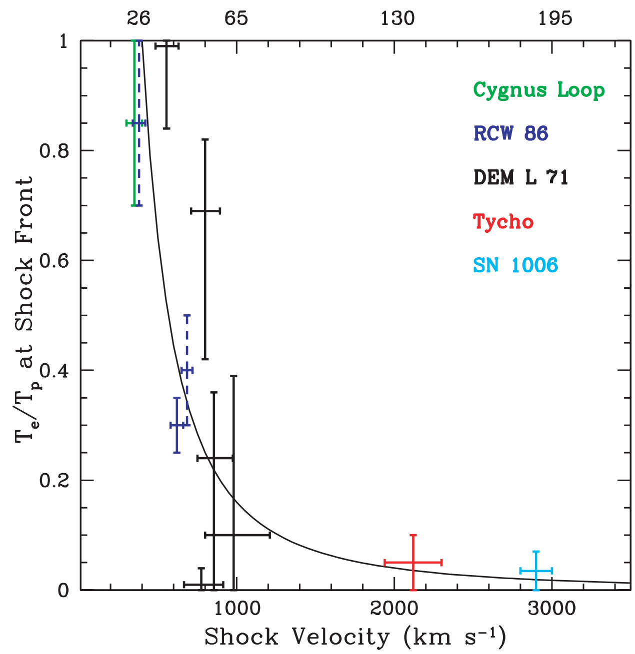


FIG. 2.—Electron to proton temperature ratio at the shock front as a function of shock velocity for five Balmer-dominated SNRs. Magnetosonic Mach numbers ($M_S$) appropriate for typical ISM conditions are indicated along the top axis. The data shown here were measured from Balmer-dominated shocks in the Cygnus Loop, RCW 86, Tycho's SNR (Ghavamian et al. 2001), SN 1006 (Ghavamian et al. 2002), and DEM L71 (Rakowski et al. 2003; Rakowski 2005). The dashed error bars for RCW 86 mark previously unpublished results. Below 400 km s$^{-1}$ ($M_S \approx 30$), the data are consistent with $(T_e/T_p)_0 = 1$. The prediction of the proposed lower hybrid wave-heating mechanism in the cosmic ray precursor, $(T_e/T_p)_0 \propto V_S^{-2}$ ($\propto M_S^{-2}$), is shown for $v_S > 400$ km s$^{-1}$.

$I_B/I_N = 1.0 \pm 0.2$] and the northern rim [$v_{\rm FWHM}({\rm H}\alpha) = 325 \pm 10$ km s$^{-1}$; $I_B/I_N = 1.06 \pm 0.1$] of RCW 86. In the fifth SNR of our sample, DEM L71 (Ghavamian et al. 2003), we used the broad component Hα width only to constrain the range of shock speeds and the proton temperature $T_p$, due to the anomalously low $I_B/I_N$ values in this SNR (see below). We then combined this information with $T_e$ measured from *Chandra* X-ray spectra of the blast wave to obtain $(T_e/T_p)_0$ (Rakowski et al. 2003; Rakowski 2005).

Although the equilibrations were obtained from different SNRs in a range of environments and distances, they show a clear trend of decreasing $(T_e/T_p)_0$ with $v_S$. The plot in Figure 2 suggests that a transitional shock speed exists around 400 km s$^{-1}$, below which collisionless processes promptly equilibrate the electrons and protons at the shock front. Above that speed, $(T_e/T_p)_0$ rapidly declines, eventually reaching values consistent with mass-proportional heating. This decline appears to follow $(T_e/T_p)_0 \propto v_S^{-2}$. We show that this behavior is predicted by a physical model of electron heating, where the electrons are heated in the cosmic ray precursor to a level that is nearly independent of shock speed before acquiring the mass-proportional increment at the shock front. The protons, on the other hand, receive only mass-proportional heating, resulting in the inverse squared dependence of equilibration on shock speed. Note that while our proposed model relies on the acceleration of cosmic rays and the existence of a cosmic ray precursor to heat the electrons, it does not require the energetics of the shock to be dominated by the cosmic rays.

In physical models, the strength of the (assumed quasi-perpendicular) shock is characterized not by the shock speed but rather by the magnetosonic Mach number $M_S$ ($\equiv v_S/v_{\rm MS}$, where $v_{\rm MS} \equiv (c_S^2 + v_{\rm A}^2)^{1/2}$ is the magnetosonic speed, $c_S$ is the sound speed ($=[(5/3)(P/\rho)]^{1/2}$) and $v_{\rm A}$ [$\equiv B/(4\pi\rho_i)^{1/2}$] is the Alfvén speed of the preshock gas). The preshock temperature, ion density, and magnetic field strength are not strongly constrained in the observed Balmer-dominated shocks. In particular, $M_S$ is most sensitive to the choice of preshock magnetic field due to the dependence of the Alfvén speed on $B^2$. However, if we assume standard values for the warm neutral interstellar medium (ISM)—preshock temperature of 10,000 K, density of 1 cm$^{-3}$, magnetic field strength of 3 $\mu$G, and 50% preshock ionization—the magnetosonic speed is then approximately 13 km s$^{-1}$. The corresponding values of $M_S$ are marked at the top of Figure 2.

## 3. LOWER HYBRID WAVE HEATING MODEL

The constant electron heating with shock velocity [giving $(T_e/T_p)_0 \propto v_S^{-2}$] suggests a process occurring in the preshock medium rather than the shock front itself. Waves in the preshock medium can be excited by shock-reflected ions, which gyrate around the field lines before returning to the shock itself, or by a cosmic ray precursor. Cargill & Papadopoulos (1988) performed hybrid simulations of the first possibility, wherein shock-reflected ions generate Langmuir and ion-acoustic waves ahead of the shock, which then heat electrons as they are damped. They predicted a temperature ratio $(T_e/T_p)_0 \sim 0.2$ nearly independent of shock velocity, a result that clearly disagrees with the observational data in Figure 2. Laming (2001a, 2001b) modeled the excitation of lower hybrid waves by shock-reflected ions, following the suggestion of McClements et al.

(1997) that lower hybrid waves could stream away from the shock with a group velocity equal to the shock velocity. In this way, waves stay in contact with the shock for arbitrarily long periods of time and hence can grow to large intensities despite low intrinsic growth rates. The electron heating predicted by such a model (Vink & Laming 2003) depends on the product of the maximum electron energy and the fraction of electrons that are resonant with the waves that can be accelerated. This gives $(T_e/T_p)_0 \propto v_S^{-1} \exp(-M^2)$, where $M$ is the shock Mach number.

Here we explore another approach. Cosmic rays have been long known to generate waves upstream of shocks; the generation of Alfvén waves is an intrinsic part of cosmic ray acceleration models. Drury & Falle (1986) showed that the negative gradient of cosmic pressure with distance ahead of the shock can generate sound waves via the "Drury instability." This is the mechanism that smooths out the hydrodynamical jump in cosmic ray modified shocks. Mikhailovskii (1992) gives a corresponding expression for the excitation of magnetoacoustic waves. We argue that the high-frequency extension of such processes by the cosmic ray pressure gradient would be the excitation of lower hybrid waves. The frequencies of these waves would lie between the gyrofrequencies of the electrons and the protons, with electron heating occurring as the waves damp along magnetic field lines. Without calculating the growth rate of the lower hybrid waves explicitly, we can estimate the magnitude of the electron heating. The parallel diffusion coefficient for electrons in lower hybrid wave turbulence is (derived from eqs. [10.83] and [10.93] of Melrose 1986; see also Begelman & Chiueh 1988)

$$D_{\parallel\parallel} = \frac{1}{4}\left(\frac{q\delta E}{m_e}\right)^2 \frac{\omega^2}{k_\perp^2 v_\parallel^2 k_\parallel v_\parallel} = \frac{1}{4}\left(\frac{q\delta E}{m_e}\right)^2 \frac{k_\parallel^2}{k_\perp^2}\frac{1}{\omega}, \qquad (1)$$

where $\omega = (\Omega_e\Omega_p)^{1/2}$ is the lower hybrid wave frequency, the geometric mean of the electron and proton cyclotron frequencies ($\Omega_{e,p} \equiv eB/m_{e,p}c$), and $k_\parallel$ and $k_\perp$ are wavevectors parallel and perpendicular to the magnetic field. Taking $\delta E = B(\Omega_p/\omega)^{1/3}(\omega/4k_\perp c)$ (Karney 1978), $k_\parallel^2/k_\perp^2 = m_e/m_p$, and the time spent by an electron inside the cosmic ray precursor $t \sim \kappa/v_S^2$, where $\kappa$ is the cosmic ray diffusion coefficient, we find

$$\frac{1}{2}mv_e^2 = \frac{1}{2}mD_{\parallel\parallel}t = \frac{m_e}{128}\left(\frac{qB}{m_e}\right)^2\left(\frac{\Omega_p}{\omega}\right)^{2/3}\frac{\omega^2}{k_\perp^2c^2}\frac{m_e}{m_p}\frac{1}{\omega}\frac{\kappa}{v_S^2}$$

$$= \frac{m_e}{128}\Omega_e\left(\frac{\Omega_p}{\omega}\right)^{5/3}\frac{\omega^2}{k_\perp^2 v_S^2}\kappa. \qquad (2)$$

If the lower hybrid wave group velocity $\partial\omega/\partial k_\perp = v_S$, then the phase velocity $\omega/k_\perp = 2v_S$ when $k_\parallel^2/k_\perp^2 = m_e/m_p$ (Laming 2001a), and the electron heating depends on a few constants times the product $\Omega_e\kappa$. Thus, for a Bohm-like cosmic ray diffusion coefficient $\kappa \propto 1/B$ and independent of $v_S$, we have an electron heating process independent of both the shock velocity and the upstream magnetic field, and $(T_e/T_p)_0 \propto v_S^{-2}$ as required. This estimate neglects the fact that only electrons with velocity greater than $v_e \sim \omega/k_\parallel$ may be heated by the waves. However, for the likely depth of a cosmic ray precursor (estimated below), the electrons will have sufficient time to at least partially collisionally equilibrate among themselves before crossing the shock, allowing a much larger fraction of preshock electrons to interact with the waves. The time spent by an electron inside a reflected ion precursor, as opposed to a cosmic ray precursor, would be $t \sim d/v_S \sim 1/\Omega_p$, where the precursor depth $d$ is approximately the gyroradius of a cosmic ray proton. Substituting this relation into equation (2) gives $(T_e/T_p)_0$, independent of $v_S$, similar to the behavior predicted by Cargill & Papadopoulos (1988), although these authors consider different waves. In this case, the shallowness of the reflected ion precursor prevents the collisional redistribution of energy among the electrons.

If a constant kinetic energy is imparted to electrons by lower hybrid waves, then for shock speeds of 400 km s$^{-1}$ and above (cf. Fig. 2) the observations require $m_e v_e^2/2 \sim 4 \times 10^{-10}$ ergs (~0.3 keV) immediately behind the shock front. In that case, we infer $\Omega_e\kappa \simeq 7 \times 10^{21}$ cm$^2$ s$^{-2}$, and $\kappa \sim 4 \times 10^{14}/B$ cm$^2$ s$^{-1}$. For typical magnetic fields $B \sim 3\ \mu$G, $\kappa$ is several orders of magnitude below that inferred for the undisturbed ISM but entirely consistent with values estimated for the solar wind or interplanetary medium. We emphasize that this estimate is a lower limit on $\kappa$. This estimate neglects the electron-electron collisional equilibration necessary to bring more electrons into resonance with the turbulence. Furthermore, lower hybrid waves can only be excited in the cosmic ray precursor if the cosmic ray pressure gradient is sufficiently strong. The required gradient scale lengths are $1/L > 8c_S/3\kappa$ for sound waves (Drury & Falle 1986) and $1/L > v_A/cr_g \sim v_A/\kappa$ for magnetoacoustic waves (Mikhailovskii 1992), where $r_g$ is the gyroradius of a cosmic ray proton. An upper limit on $\kappa$ will come from the requirement that the neutral H survive against electron impact ionization in the precursor to reach the shock front. Numerically, $\kappa \lesssim 10^{24}(v_S/1000\ \mathrm{km\ s^{-1}})^2/n_e$ cm$^2$ s$^{-1}$. Further constraints on the cosmic ray diffusion coefficient and pressure will be obtained from calculation of the lower hybrid wave growth rate required to sustain the electron heating. This growth rate must be significantly larger than the charge exchange frequency of the partially neutral gas. Under typical ISM conditions, $(\Omega_e\Omega_p)^{1/2} \sim 1$ Hz and $n_{\mathrm{H}^0}\langle\sigma_{cx}v\rangle \sim 10^{-8}$ Hz, so the condition for electron heating is nearly always satisfied.

The electron heating by lower hybrid waves is inherently anisotropic. If some of this anisotropy survives the electron-electron collision equilibration, a polarization signal may be present in the narrow component of H$\alpha$ (see, e.g., Laming 1990), which might provide more insight into the electron heating process.

## 4. THE WIDTH OF THE H$\alpha$ NARROW COMPONENT

The same cosmic ray precursor should also generate lower frequency waves, which for a quasi-perpendicular shock will include magnetoacoustic waves. Below the ion-neutral charge exchange frequency, these waves are not effectively damped (Drury et al. 1996) and may reveal themselves via broadening of the narrow H$\alpha$ component (Smith et al. 1994). Those authors suggested that waves in the cosmic ray precursor actually heat the preshock gas to 30,000–40,000 K and that the observed line width is thermal in nature. An upper limit to the cosmic ray diffusion coefficient of ~$10^{24}/n_e$ cm$^2$ s$^{-1}$ then results from the constraint that sufficient neutral H survive passage through the precursor to encounter the shock. However, no precise heating mechanism was specified, and we now suggest that the large width of the narrow component H$\alpha$ line in the observed SNRs is not of thermal origin but rather due to the motion of protons in the lowest frequency waves of the magnetoacoustic spectrum. These waves lie below the charge exchange frequency, allowing a coherent oscillation of preshock neutrals and preshock protons. In this case, $\delta v \simeq v_A\delta B/B$ for Alfvén waves ($v_A$ should be replaced by $v_{MS}$ for magnetoacoustic waves). The Alfvén speed upstream

from the shock is in the range 1–10 km $s^{-1}$, so an observed broadening $\delta v/v_A > 1$ also implies $\delta B/B > 1$. Such a magnetic field amplification has already been proposed in the context of cosmic ray acceleration in shocks (Lucek & Bell 2000; Bell & Lucek 2001). A successful model of precursor ions will need to reproduce the existing measurements of narrow-component Hα line widths (Smith et al. 1994; Hester et al. 1994; Sollerman et al. 2003), which indicate that they remain relatively constant (30–50 km $s^{-1}$) over a wide range in shock speed (180–3000 km $s^{-1}$). We defer this topic to future work.

## 5. DISCUSSION AND SUMMARY

The plot of $(T_e/T_p)_0$ in Figure 2 is qualitatively similar to results of a survey of electron heating at solar wind shocks (Schwartz et al. 1988). The main difference is that $T_e \sim T_i$ is obtained for Alfvénic Mach numbers ≲5 in the solar wind, whereas in Figure 2 this occurs for magnetosonic Mach numbers around 20–30, for assumed preshock magnetic fields of 3 μG. A preshock magnetic field amplification in SNRs, of a similar amount required to reproduce the width of the Hα narrow component ($\delta B/B \sim 5$–10), would shift the $(T_e/T_p)_0$ ratios in Figure 2 onto Mach numbers similar to those in the solar wind. This may support our interpretation. Collisionless shocks play a dominant role in heating the intergalactic medium (IGM) during large-scale structure formation (Ryu et al. 2003; Yoshida et al. 2005; Kang et al. 2005). If the preshock magnetic field is amplified as described above, then the relationship $(T_e/T_p)_0 \propto M_S^{-2}$ may also be applicable to modeling the ionization and temperature structure of the IGM.

The maximum energy attainable by cosmic rays in Balmer-dominated shocks is limited by ion-neutral damping to ∼0.1–1 TeV (Drury et al. 1996). It is possible that the shocks with stronger cosmic ray acceleration generate sufficient electron heating in their precursors that no neutrals survive to cross the shock. The anomalously low $I_B/I_N$ ratio observed in DEM L71 (Ghavamian et al. 2003) may indicate that this is an intermediate case. Electron heating in a shock precursor will produce added narrow-component Hα. However, since the broad component can only arise by charge exchange with shocked protons, the neutral H must penetrate either the shock or the reflected ion precursor. We emphasize that of the points plotted in Figure 2 from Hα $I_B/I_N$ measurements, the electron temperatures from RCW 86 (Vink et al. 2006), the Cygnus Loop (Levenson et al. 2002), SN 1006 (Laming et al. 1996; Vink et al. 2003), and Tycho (Hwang et al. 2002; Warren et al. 2005) have been independently corroborated by measurements in other wave bands.

Several lingering questions remain from Figure 2: What mechanism causes the prompt electron-proton equilibration below 400 km $s^{-1}$, and why does the decline in $(T_e/T_p)_0$ begin at that shock speed? Even more importantly, does the inverse square relationship between equilibration and shock speed/Mach number also hold for collisionless shocks in fully ionized gas? These issues will be addressed in future work.

P. G. would like to thank R. Cen and K. Sembach for helpful discussions and acknowledges support from NASA contract NAS8-03060. J. M. L. and C. E. R. acknowledge support from NASA contract NNH06AD66I (LTSA Program) and basic research funds of the Office of Naval Research.

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